

# Discovering the missing bright quasars at intermediate redshifts based on the optical/near-IR color selections

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## ABSTRACT

The identifications of quasars at intermediate redshifts ( $2.2 < z < 3.5$ ) are inefficient in previous quasar surveys as their optical colors are similar as those of stars. The near-IR K-band excess technique has been suggested to overcome this difficulty. Our recent study also proposed to use the optical/near-IR colors for selecting  $z < 4$  quasars. To verify the effectiveness of this method, we selected a list of unidentified bright targets with  $i \leq 18.5$  from the quasar candidates of SDSS DR6 with both SDSS *ugriz* optical and UKIDSS YJHK near-IR photometric data, which satisfy our proposed Y-K/g-z criterion and have photometric redshifts between 2.2 and 3.5 estimated from the 9-band SDSS-UKIDSS data. 43 of them were observed with the BFOSC instrument on the 2.16m optical telescope at Xinglong station of NAOC in the spring of 2012. 35 of them were spectroscopically identified as quasars with redshifts between 2.1 and 3.4. The high success rate of discovering these missing quasars in the SDSS spectroscopic surveyed area further demonstrates the robustness of both the Y-K/g-z selection criterion and the photometric redshift estimation technique. We also used the above criterion to investigate the possible star contamination rate to the quasar candidates of SDSS DR6, and found that it is much higher in selecting  $3 < z < 3.5$  quasar candidates than the lower redshift ones. The significant improvement in the photometric redshift estimation by using the 9-band SDSS-UKIDSS data than using the 5-band SDSS data is demonstrated and a catalog of 7727 unidentified quasar candidates in SDSS DR6 selected with the optical/near-IR colors and with photometric redshifts between 2.2 and 3.5 is provided. We discuss the implications of our results to the ongoing and upcoming large optical and near-IR sky surveys.

*Subject headings:* galaxies: active — galaxies:high-redshift — quasars: general — quasars: emission lines

## 1. Introduction

Quasars are important extragalactic objects in astrophysics due to their unusual properties. They not only can be used to probe the physics of supermassive black holes and accretion/jet process, but also are closely related to the studies of galaxy evolution, intergalactic medium, large scale structure and cosmology. The number of quasars has increased steadily since its discovery (Schmidt 1963). Especially, a large number of quasars have been discovered in two large spectroscopic surveys, namely, the Two-Degree Fields (2DF) survey (Boyle et al. 2000) and the Sloan Digital Sky Survey (SDSS) (York et al. 2000). 2DF mainly selected low redshift ( $z < 2.2$ ) quasar candidates with UV-excess (Smith et al. 2005) and has discovered more than 20,000 blue quasars (Croom et al. 2004). SDSS adopted a multi-band optical color selection method for quasars mainly by excluding the point sources in the stellar locus of the optical color-color diagrams (Richards et al. 2002) and has identified more than 120,000 quasars (Schneider et al. 2010). 90% of SDSS quasars have low redshifts ( $z < 2.2$ ), though some dedicated methods were also proposed for finding high redshift quasars ( $z > 3.5$ ) (Fan et al. 2001a,b; Richards et al. 2002).

However, in the redshift range  $2.2 < z < 3.5$ , the selection of SDSS quasars is inefficient. Richards et al. (2006) have demonstrated this problem by checking the efficiency of SDSS quasar selection with the FIRST radio quasars and found that the efficiency drops substantially in the range  $2.2 < z < 3.5$ . There are two remarkable dips, one around  $z = 2.8$  and another around  $z = 3.4$ . The reason for this problem is well understood. At redshift  $2.2 < z < 3.5$ , the spectral energy distributions of quasars show similar optical colors to that of normal stars, and quasar selections using the optical color-color diagrams become very inefficient due to the serious contaminations of stars (Fan 1999; Richards et al. 2002; 2006; Schneider et al. 2007; Hennawi et al. 2010). Because of the crucial importance of  $z > 2.2$  quasars in studying the Ly $\alpha$  forest and cosmic baryon acoustic oscillation (BAO) (White 2003; McDonald & Eisenstein 2007) and in constructing the accurate luminosity function to study the quasar evolution in the mid-redshift universe (Wolf et al. 2003; Jiang et al. 2006), we need to explore other more efficient ways than using the optical colors alone to identify the missing  $2.2 < z < 3.5$  quasars. We noticed that significant efforts have been made recently for the quasar target selections in the SDSS-III Baryon Oscillation Spectroscopic Survey (BOSS; Eisenstein et al. 2011, Ross et al. 2012)

The first possible way to identify the missing  $2.2 < z < 3.5$  quasars is to use optical variability, as this is one of the well known quasar properties (Hook et al. 1994; Cristiani et al. 1996; Giveon et al. 1999). Selecting quasars based on variability is obviously not biased to the optical colors. Recently, Schmidt et al. (2010), MacLeod et al. (2011) and Butler & Bloom (2011) have proposed to select quasar candidates by constructing various

intrinsic variability parameters from the light-curves of known quasars in SDSS Stripe 82 (hereafter S82; see also Sesar et al. 2007). They claimed that with their methods they can efficiently separate quasars from stars and achieve substantially increase of the number of quasars at  $2.5 < z < 3.0$ . In addition, recent results from the SDSS-III/BOSS (Eisenstein et al. 2011) also confirmed the high success rate of spectroscopically identifying variability selected quasars, which leads to a significant increase of  $z > 2.2$  quasar density in S82 than that based on optical color selected quasars (Palanque-Delabrouille et al. 2011; Ross et al. 2012). However, only for very limited sky areas the multi-epoch observations have been done, so the variability methods in general can not be used for selecting quasars over a large sky area.

The second possible way for separating  $z > 2.2$  quasars from stars is to utilize their near-IR colors. Due to the difference in physics mechanisms, the continuum emission from stars usually decreases more rapidly from optical to the near-IR wavelengths than that of quasars, and result in the color differences in near-IR between stars and quasars. This leads to a K-band excess technique for identifying quasars at  $z > 2.2$  (eg. Warren, Hewett & Foltz 2000; Croom, Warren & Glazebrook 2001; Sharp et al. 2002; Hewett et al. 2006; Chiu et al. 2007; Maddox et al. 2008; Smail et al. 2008; Wu & Jia 2010). Based on a sample of 8498 quasars and a sample of 8996 stars compiled from the photometric data in the *ugriz* bands of SDSS and YJHK bands of UKIRT InfraRed Deep Sky Surveys (UKIDSS<sup>1</sup>), Wu & Jia (2010) proposed an efficient empirical criterion, (i.e.  $Y - K > 0.46(g - z) + 0.82$ , where YK magnitudes are Vega magnitudes and  $gz$  magnitudes are AB magnitudes) for selecting  $z < 4$  quasars. A check with the FIRST (Becker, White & Helfand 1995) radio-detected SDSS quasars, which are free of the color selection bias, also proved that with this Y-K/g-z criterion they can achieve the completeness higher than 95% for these radio-detected quasars with  $z < 3.5$ , which seems to be difficult when using the SDSS optical color selection criteria alone where two dips around  $z \sim 2.7$  and  $z \sim 3.4$  obviously exist (Richards et al. 2002, 2006; Schneider et al. 2007, 2010). Recently, Peth, Ross & Schneider (2011) extended the study of Wu & Jia (2010) to a larger sample of 130,000 SDSS-UKIDSS selected quasar candidates and re-examined the near-IR/optical colors of them.

Although by combining the variability and optical/near-IR color we may achieve the maximum efficiency in identifying  $2.2 < z < 3.5$  quasars (Wu et al. 2011), for most sky areas we still lack of variability data. One may also think of using radio and X-ray data, but these can only be helpful for selecting specific quasar samples (White et al. 2000; Green et al.

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<sup>1</sup> The UKIDSS project is defined in Lawrence et al. (2007). UKIDSS uses the UKIRT Wide Field Camera (WFCAM; Casali et al. 2007) and a photometric system described in Hewett et al. (2006). The pipeline processing and science archive are described in Hambly et al. (2008).

1995), which represent only a small fraction of the quasar population. Therefore, using the optical/near-IR colors is probably still the most important way for selecting  $2.2 < z < 3.5$  quasars. Although we have done some observations to identify the  $z > 2.2$  quasars (Wu et al. 2010a,b; Wu et al. 2011), more efforts are still needed to check whether using our Y-K/g-z criterion can help us to discover more missing quasars at  $2.2 < z < 3.5$ , especially in the SDSS spectroscopically surveyed area.

The paper is organized as follows. In Section 2 we will describe the target selections and spectroscopic observations, and report our discovery of 35 new  $2.2 < z < 3.5$  quasars. In section 3 we will use our Y-K/g-z criterion to check the possible contaminations of stars in the quasar candidate catalog of SDSS DR6 and investigate the improvement in the photometric redshift estimation by using the 9-band SDSS-UKIDSS data. We will discuss our results and their implications in Section 4.

## 2. Target selections and spectroscopic observations

The main purpose of our study is to use our proposed Y-K/g-z criterion to discover more missing quasars at  $2.2 < z < 3.5$  in the SDSS spectroscopically surveyed area. We started from the 1 million quasar candidates in SDSS DR6 given by Richards et al. (2009) (hereafter R09) from the Bayesian classification, and selected the unidentified quasar candidates brighter than  $i = 18.5$  and with the photometric redshifts given in R09 greater than 2.2 and the redshift probability higher than 0.5. Then we cross-matched these quasar candidates with the UKIDSS/Large Area Survey(LAS) DR7 using a position offset within  $3''$  and got 401 candidates with both SDSS *ugriz* and UKIDSS YJHK photometric data. 126 of them satisfy our  $Y - K > 0.46(g - z) + 0.82$  criterion for selecting  $z < 4$  quasars (Wu & Jia 2010). 17 among these 126 candidates have been spectroscopically identified as quasars after the SDSS DR6, and 15 of them have redshifts greater than 2.2. Another one candidate was identified as a white dwarf. After excluding these 18 known objects, we got a list of 108 quasar candidates.

Since these quasar candidates have 9-band SDSS and UKIDSS photometric data, the photometric redshifts obtained from these 9-band data have shown to be more accurate than those given by the 5-band SDSS photometric data (Wu & Jia 2010). We use our developed program to estimate the photometric redshifts based on the 9-band data and found that 15 objects among 108 quasar candidates have photometric redshifts smaller than 2, while for other quasar candidates our results are consistent with those obtained in R09 from the SDSS photometric data. After excluding these 15 objects, we get a target list of 93 quasar candidates with reliable photometric redshifts between 2.2 and 3.6. After the public release

of UKIDSS/LAS DR8 in April, 2012, we also added other 12 quasar candidates, which have UKIDSS/LAS DR8 data but were not included in the UKIDSS/LAS DR7, making our final list including 105 quasar candidates.

Among these 105 quasar candidates, 92 have Right Ascension (RA) between 7hr and 17hr. In March to May of 2012, we made 8-night spectroscopic observations on 43 among these 92 bright quasar candidates (sampling rate of 46.7%) with photometric redshifts at  $2.2 < z_{\text{ph}} < 3.5$  using the BAO Faint Object Specgraph and Camera (BFOSC) of the 2.16m optical telescope at the Xinglong station of National Astronomical Observatories, Chinese Academy of Sciences (NAOC). A low resolution grism with the dispersion of  $198\text{\AA}/\text{mm}$ , the wavelength coverage from 3850 to 7000 $\text{\AA}$ , and the spectral resolution of  $2.97\text{\AA}$  was used. During our observations, the typical seeing varied from  $1.5''$  to  $2.5''$ , so we adopted the long slit width of  $1.8''$  and  $3.6''$  accordingly (no choice in between). In Table 1 we summarize the parameters and details of the observations for these 43 quasar candidates, including the name, observation date, exposure time, SDSS and UKIDSS magnitudes, photometric redshift, identification result and the spectral redshift.

For the 43 quasar candidates, 35 were spectroscopically identified as quasars with redshifts from 2.1 to 3.4, 3 were identified as stars and 5 were unidentified due to the lower signal-to-noise ratios of their spectra. The spectra of 35 new quasars, after the standard flat-field corrections, flux and wavelength calibrations, were plotted in Fig. 1.

The spectra of these quasars were analysed according to the following procedures. First the spectra were redshift corrected to the rest-frame and were corrected for the Galactic extinction using the extinction map of (Schlegel et al. 1998). They are then fitted based on an IDL code MPFIT (Markwardt 2009). We fitted the spectra with the pseudo-continuum model consisting of the featureless nonstellar continuum and FeII emissions. The featureless nonstellar continuum is assumed to be a power-law, so two free parameters (the amplitude and the slope) are required. Templates for FeII emissions have been constructed from the spectrum of the narrow-line Seyfert 1 galaxy, I Zw 1. We used the UV template generated by Vestergaard & Wilkes (2001) and Tsuzuki et al. (2006) in the wavelength range of 1000-3500 $\text{\AA}$ . The UV FeII template was convolved with a velocity dispersion and shifted with a velocity, assuming the line width of FeII lines is the same with emission lines in the corresponding wavelength range.

After constructing the pseudo-continuum, the CIV line should be fitted with two Gaussians, one for the narrow component and another for the broad component. However, as the spectra of most quasars have low signal-to-noise ratio, we used only one Gaussian to fit the CIV emission line. The absorption features are evident in a few quasars, so one more negative Gaussian is added in the fitting. We measured the Full Width at Half Maximum

of CIV line (FWHM(CIV)), luminosity at 1350Å( $L_{1350}$ ) from the spectra. The black hole mass is calculated based on FWHM(CIV) and  $L_{1350}$  with Eq.(7) in Vestergaard & Peterson (2006)(see also Kong et al. 2006). Using a scaling relation between  $L_{1350}$  and bolometric luminosity  $L_{bol}$ ,  $L_{bol} = 4.62L_{1350}$ , we estimated the bolometric luminosity for these quasars. Based on the obtained black hole mass and bolometric luminosity, we also calculated their Eddington ratios. The results are summarized in Table 2. Although we noticed that the uncertainties of these values are probably quite large due to the low spectral quality and the unusual properties of CIV, the overall properties of these quasars are consistent with those of typical SDSS quasars with redshift greater than 2.2 (Shen et al. 2011).

Among these 35 quasars, SDSS J115531.45-014611.9 is a Broad Absorption Line (BAL) quasar with redshift at  $z = 3.196$ . The blue wings of both Ly $\alpha$  and CIV emission lines are obviously absorbed. After the Galactic extinction and redshift corrections, we compare the spectrum of this BAL quasar with the SDSS composite quasar spectrum. The object shows one absorption system blueshifted from its systematic redshift of 3.196. It is evidenced by the absorption features at velocities of 18000 km/s, 15000 km/s and 22000 km/s in the blueward of the CIV, SiIV, Ly $\alpha$  emission lines respectively. The high velocities derived from the broad absorption features of these three lines are consistent with those of quasars with higher UV luminosity (Gibson et al. 2009). This is also expected if the BAL outflow is produced by the strong radiation pressure (Murray et al. 1995).

### 3. Accuracy of photometric redshifts and star contaminations in the quasar candidate catalog of SDSS DR6

We selected the quasar targets from the SDSS DR6 1 million quasar candidate catalog of R09, and used both the SDSS and UKIDSS photometric data for further selections and photometric redshift estimations. That's the main reason why we can achieve very high success rate for identifying the missing quasars with  $2.2 < z < 3.5$ . With the SDSS-UKIDSS optical/near-IR data and our proposed quasar selection criterion, we may also investigate the accuracy of photometric redshifts and the possible star contaminations in the quasar candidate catalog of SDSS DR6, which will be helpful for future spectroscopic observations.

We cross-matched the SDSS DR6 1 million quasar candidate catalog of R09 with the UKIDSS/LAS DR8 data by using the positional offset of 3" for finding only the closest counterpart, and obtained 97923 sources with full detections in SDSS and UKIDSS 9 photometric bands. This SDSS-UKIDSS quasar candidate sample is much bigger than the previous one with 42133 sources from the UKIDSS/LAS DR3 (Peth, Ross & Schneider 2011). Among these 97923 sources, there are 24878 known quasars and 73011 unidentified quasar candidates

in SDSS DR6.

First we checked the improvement of photometric redshift estimations using the 9-band SDSS-UKIDSS photometric data than using the SDSS data alone. We used our photometric redshift estimation program (Wu & Jia 2010; Wu, Zhang & Zhou 2004) to obtain the photometric redshifts of all unidentified quasar candidates and known quasars in R90 based on the SDSS-UKIDSS data, and compared them with the photometric redshifts given in R90 and the spectral redshifts for known quasars in SDSS DR6. In the two upper panels of Fig. 2, we compare the photometric redshifts in R90 and ours for 73011 unidentified quasar candidates in R09, and show the histogram distribution of their differences. For 59.8% of these unidentified quasar candidates, the differences between two kinds of photometric redshifts are less than 0.2. However, there are still obvious differences, especially when the photometric redshifts are smaller than 3. Comparing with our results, the photometric redshifts given in R09 are systematically larger for some low-redshift quasar candidates. In two middle panels and two lower panels of Fig. 2, we compare the photometric redshifts given in R90 and by us for 24878 known quasars with spectral redshifts, respectively. For 76.1% of the known quasars, R90 gave the photometric redshifts within the difference smaller than 0.2 from their spectral redshifts. By using the SDSS-UKIDSS 9-band photometric data to estimate the photometric redshifts, such a fraction increases to 85.2%. This significant improvement can be clearly observed from Fig. 2, and demonstrates again that by adding the near-IR photometric data to the SDSS optical data we can achieve substantially higher accuracy in the photometric redshift estimations (Wu & Jia 2010; Wu et al. 2012).

Next we checked the possible star contaminations in the quasar candidate catalog of SDSS DR6 (R09), using the Y-K/g-z quasar selection criterion. In Fig. 3 we show the distributions of 24878 known quasars and 73011 unidentified quasar candidates in R09 in the Y-K/g-z color-color diagram, as well as our Y-K/g-z quasar selection criterion (Wu & Jia 2010). For 24648 known  $z < 4$  quasars, using the Y-K/g-z criterion can select 24295 of them (98.6%). For 61489 unidentified quasar candidates in R09 with the photometric redshifts of  $z_{ph} < 2.2$  (we adopted the photometric redshifts estimated with the SDSS-UKIDSS 9-band photometric data), using the Y-K/g-z criterion can select 60412 of them (98.3%). For 10687 unidentified quasar candidates in R09 with the photometric redshift of  $2.2 < z_{ph} < 4$ , using the Y-K/g-z criterion can select 8934 of them (83.6%). Therefore, the quasar candidates selection in R09 are well consistent with our Y-K/g-z selection for  $z_{ph} < 2.2$  quasar candidates, but there are substantial contaminations from stars for selecting  $2.2 < z_{ph} < 4$  quasar candidates. This can be also seen from the lower panel of Fig. 3, where the green dots below the line most probably represent the star contaminations.

To better understand the quasar selection efficiency and the star contaminations at

different redshift, in Fig. 4 we plot the photometric redshift dependences of the fraction of 24648 known  $z < 4$  quasars selected by the Y-K/g-z criterion and the fraction of 72176 unidentified quasar candidates in R09 with photometric redshifts of  $z_{ph} < 4$  selected by the Y-K/g-z criterion. For known  $z < 4$  quasars, using the Y-K/g-z criterion can reach the efficiency higher than 90% at almost all redshift, except for  $z > 3.5$ . For unidentified quasar candidates, R09 selection has the similar efficiency (higher than 90%) as using the Y-K/g-z criterion for selecting  $z_{ph} < 2.6$  quasars but has higher star contaminations for selecting  $z_{ph} > 2.6$  quasars than using the Y-K/g-z criterion. One may think that the decrease of quasar selection fraction at  $z_{ph} > 2.6$  (denoted by the blue dotted line in Fig. 4) is due to both the mis-identifications of quasars as stars by the Y-K/g-z criterion and the true star contaminations. After the deduction of the mis-identification rate of quasars as stars (which can be estimated from the known quasar selection fraction denoted as the black solid line in Fig. 4) by the Y-K/g-z criterion at different redshift, we can obtain the possible star contamination rate in R09 at different redshift (denoted by the red dashed line in Fig. 4). It is clear that the star contamination rate becomes substantially higher for selecting  $z_{ph} > 2.6$  quasars than the lower redshift ones, even up to 30% to 40% for selecting quasars at redshift  $3 < z_{ph} < 3.5$ . We must notice that the real star contaminations are probably much higher than those we estimated with the Y-K/g-z criterion. Therefore, the star contamination rate in R09 we obtained for selecting  $2.6 < z_{ph} < 4$  quasars could be underestimated. In fact, based on the clustering study of Myers et al. (2006), the star contamination in the ‘mid- $z$ ’ range of R09 was estimated to be higher than 50% (Richards et al. 2009b). Nevertheless, we believe that using the Y-K/g-z criterion can help us to exclude the star contaminations significantly and obtain higher efficiency for selecting the  $2.6 < z_{ph} < 4$  quasars.

From R09, we can obtain a list of SDSS DR6 unidentified quasar candidates with UKIDSS/LAS DR8 full detections in the YJHK bands and with the photometric redshifts (given in R09) at  $2.2 \leq z_{ph}(R09) \leq 3.5$ , which consists of 17719 objects. However, if we adopt our photometric redshifts obtained from the 9-band SDSS-UKIDSS photometric data and use our Y-K/g-z criterion to do further selection, such a list consists of only 7727 quasar candidates at  $2.2 \leq z_{ph} \leq 3.5$ . The substantial decrease of the size is mainly due to the increase of photometric redshift reliability and the deduction of star contaminations by using the Y-K/g-z criterion. In Table 3 we list the name, photometric redshift, SDSS and UKIDSS magnitudes for these 7727 quasar candidates with our estimated photometric redshift at  $2.2 \leq z_{ph} \leq 3.5$ . We noticed that some of them have been identified after SDSS DR6, including this work. Future spectroscopy on these unidentified quasar candidates will provide further checks to the robustness of both the quasar selection criterion and the photometric redshift estimation presented by us.



#### 4. Discussion

We have presented the spectroscopic observations on 43 bright quasar candidates selected from R09, which have photometric redshifts at  $2.2 < z_{ph} < 3.5$  estimated from the 9-band SDSS and UKIDSS photometric data and satisfy our Y-K/g-z criterion, and successfully identified 35 of them to be real quasars with redshifts between 2.1 and 3.4. The high efficiency of spectroscopic identifications provides further support for discovering the missing quasars at such intermediate redshifts based on the optical and near-IR color selections. We also found the substantial improvement of photometric redshift estimation from using the 9-band SDSS-UKIDSS data than using the SDSS data alone. We investigated the star contamination rate of quasar candidates in R09, which could be much higher for selecting quasars at photometric redshift of  $3 < z_{ph} < 3.5$  than the lower redshift ones. By using our photometric redshifts estimated from the SDSS and UKIDSS photometric data and the Y-K/g-z criterion to exclude the star contaminations, we obtained a catalog of 7727 SDSS-UKIDSS unidentified quasar candidates with photometric redshift at  $2.2 < z_{ph} < 3.5$ . The ongoing and future spectroscopic observations, such as SDSS-III/BOSS (Eisenstein et al. 2011), will provide further check to the robustness of this catalog, though the UKIDSS near-IR data were not used for selecting the majority of quasar candidates in BOSS (Ross et al. 2012).

Since UKIDSS only covers a very limited sky area, we still need much deeper optical/near-IR photometry in a larger sky area for taking the full advantages of the optical/near-IR color for selecting quasars, especially for  $z > 2.2$  quasars. The recently released Wide-field Infrared Survey Explorer (WISE) all-sky data (Wright et al. 2010) also provided abundant photometric data in the near(middle)-IR bands, which will be very helpful for quasar selections (Wu et al. 2012; Stern et al. 2012; Edelson & Malkan 2012). Fortunately, several ongoing optical and near-IR photometric sky surveys will also provide us further opportunities to apply our optical/near-IR color selections of quasars to larger and deeper fields. In addition to SDSS III (Eisenstein et al. 2011), which has taken 2500 deg<sup>2</sup> further imaging in the south galactic cap, the SkyMapper (Keller et al. 2007) and Dark Energy Survey (DES; The Dark Energy Survey Collaboration 2005) will also present the multi-band optical photometry in 20000/5000 deg<sup>2</sup> of the southern sky, with the magnitude limit of 22/24 mag in *i*-band, respectively. The Visible and Infrared Survey Telescope for Astronomy (VISTA; Arnaboldi et al. 2007) is carrying out the VISTA Hemisphere Survey (VHS) in the near-IR YJHK bands for 20000 deg<sup>2</sup> of the southern sky with a magnitude limit at K=20.0, which is about five and two magnitude deeper than the Two Micron ALL Sky Survey (2MASS; Skrutskie et al. 2006) and UKIDSS/LAS limits (Lawrence et al. 2007), respectively. Therefore, the optical and near-IR photometric data obtained with these ongoing surveys will provide us a large database for quasar selections. Needless to say, the ongoing Panoramic Survey Tele-

scope & Rapid Response System (Pan-STARRS; Kaiser et al. 2002) and the future Large Synoptic Survey Telescope (LSST; Ivezić et al. 2008) will also provide us with multi-epoch photometry in multi-bands covering a large area of the sky, which will undoubtedly help us to construct a much larger sample of quasars based on both optical/near-IR colors and variability features.

On the other hand, the spectroscopic observations are still crucial to determine the quasar nature and redshifts for the quasar candidates selected from the optical/near-IR colors. The ongoing SDSS-III/BOSS is expected to obtain the spectra of 150000 quasars at  $2.2 < z < 4$  (Eisenstein et al. 2011; Ross et al. 2011). We believe that many  $2.2 < z < 3.0$  quasars, including the candidates we listed in this paper, should be spectroscopically identified by BOSS. In addition, the Chinese GuoShouJing telescope (LAMOST; Su et al. 1998; Zhao et al. 2012), a spectroscopic telescope with 4000 fibers, which is currently in the final stage of commissioning and will start the regular spectroscopic survey in the fall of 2012, is also aiming at discovering 0.3 million quasars from 1 million candidates with magnitudes brighter than  $i = 20.5$  in the next 5 years (Wu et al. 2010a,b; Wu 2011). By using the optical/near-IR colors, we hope large input catalogs of reliable quasar candidates will be provided to these quasar surveys for future spectroscopic observations. We expect that a much larger and more complete quasar sample covering a wider range of redshift will be constructed in the near future.

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Table 1: Parameters and observation details of 43 quasar candidates

Name (SDSS J)	Date	Exposure (s)	u	g	r	i	z	Y	J	H	K	$z_{\text{ph}}(\text{R09})$	$z_{\text{ph}}$	Result	$z_{\text{sp}}$
075746.08+232054.2	2012-03-13	3600	19.06	18.46	18.48	18.47	18.27	17.69	17.39	16.82	16.02	2.365	2.375	F star	
081545.72+264847.1	2012-04-14	1800	18.27	17.14	17.06	17.04	16.87	16.24	15.86	15.5	15.29	2.755	2.825	F star	
081617.55+225604.5	2012-05-15	2400	19.95	18.63	18.43	18.35	18.35	17.74	17.37	16.92	16.57	2.905	2.875	quasar	2.931
083255.70+004710.1	2012-03-13	3600	19.80	18.40	18.29	18.30	18.28	17.89	17.36	16.92	16.54	2.905	2.875	quasar	2.919
084659.42+253940.9	2012-04-16	3600	19.75	18.44	18.46	18.43	18.25	17.46	17.03	16.53	15.99	2.795	2.875	quasar	2.892
085152.98+091808.5	2012-05-16	3600	18.65	18.13	17.95	17.94	17.79	17.15	16.95	16.54	15.85	2.505	2.575	low S/N	
085825.51+283258.5	2012-03-13	3600	20.54	18.73	18.44	18.50	18.49	17.68	17.20	16.74	16.15	3.535	2.975	quasar	3.226
090233.19+034131.2	2012-05-17	3600	18.49	17.92	17.79	17.77	17.6	17.06	16.88	16.39	15.63	2.465	2.575	quasar	2.532
090827.71+011322.5	2012-04-15	2400	18.33	17.64	17.54	17.47	17.29	16.83	16.51	16.07	15.26	2.565	2.325	quasar	2.083
091756.58+100836.7	2012-04-16	2400	18.54	17.72	17.68	17.67	17.58	16.9	16.55	16.1	15.67	2.695	2.675	quasar	2.760
091857.36+025205.4	2012-04-15	3000	19.39	17.9	17.79	17.72	17.61	17.06	16.75	16.39	15.9	2.905	2.875	quasar	2.789
092021.02+020113.7	2012-03-14	3600	19.96	18.58	18.51	18.46	18.44	17.76	17.45	17.15	16.71	2.905	2.875	quasar	2.826
093655.11+305855.3	2012-05-17	2700	20.37	18.55	18.45	18.49	18.37	17.50	17.31	16.8	16.37	2.945	2.875	quasar	3.005
094137.09+102650.9	2012-04-16	2700	18.67	18.04	17.90	17.9	17.75	17.01	16.77	16.38	15.84	2.535	2.625	quasar	2.584
095118.43+083959.9	2012-03-13	3600	18.90	18.25	18.21	18.19	18.02	17.50	17.18	16.64	15.85	2.365	2.375	quasar	2.523
100834.73+022302.5	2012-04-14	3600	19.93	18.13	17.91	17.88	17.85	17.39	16.95	16.54	16.01	3.005	2.975	quasar	3.086
103301.49+065106.5	2012-05-16	2700	18.73	18.03	17.91	17.84	17.69	17.15	16.88	16.45	16.05	2.565	2.625	quasar	2.637
114608.05+094216.5	2012-05-15	5400	19.54	18.49	18.49	18.38	17.96	17.05	16.83	16.22	15.35	2.615	2.475	quasar	2.580
115531.45+014611.9	2012-03-13	6000	23.25	19.36	18.91	18.50	18.50	17.94	17.39	17.00	16.36	3.495	3.350	quasar(BAL)	3.196
121510.62+142834.5	2012-04-15	3600	19.20	18.45	18.34	18.33	18.15	17.47	17.20	16.75	16.11	2.595	2.675	quasar	2.480
122043.86+011122.1	2012-05-17	3600	19.21	18.39	18.38	18.27	18.00	17.20	16.86	16.31	15.61	2.395	2.725	quasar	2.565
122619.73+104953.5	2012-04-15	3600	19.06	18.35	18.27	18.27	18.10	17.49	17.23	16.78	16.12	2.565	2.625	quasar	2.375
124605.36+071128.2	2012-03-14	3600	19.20	18.56	17.82	17.52	17.33	16.88	16.55	15.97	15.25	3.435	3.550	quasar	2.044
125934.29+075200.7	2012-05-16	2700	18.29	17.78	17.67	17.68	17.63	17.2	16.93	16.45	15.93	2.475	2.625	quasar	2.370
130318.32+030809.4	2012-04-14	2700	18.39	17.65	17.58	17.47	17.35	16.6	16.25	15.87	15.37	2.595	2.675	quasar	2.664
131008.67+084405.0	2012-04-16	2700	18.48	17.85	17.73	17.72	17.63	17.15	16.92	16.43	15.85	2.535	2.625	quasar	2.232
135942.50+022426.0	2012-03-14	3600	24.10	18.82	18.33	18.29	18.18	17.69	17.26	16.85	16.33	3.475	3.350	quasar	3.265
142405.57+044105.5	2012-05-16	3600	18.72	18.17	18.01	18.01	17.83	17.36	17.09	16.50	15.89	2.465	2.625	quasar	2.232
142543.33+024759.8	2012-04-15	2700	18.48	17.79	17.77	17.75	17.67	16.94	16.65	16.16	15.70	2.605	2.675	quasar	2.689
142854.09+132259.0	2012-05-17	5400	20.89	19.46	18.94	18.37	18.10	17.26	16.86	16.38	15.83	2.735	2.925	quasar	3.093
144526.15+023906.8	2012-05-15	3600	19.05	18.00	18.00	17.95	17.78	17.24	16.91	16.46	15.98	2.695	2.675	quasar	2.706
145230.38+130227.3	2012-05-17	2700	18.26	17.77	17.65	17.68	17.51	16.81	16.58	16.03	15.33	2.465	2.525	quasar	2.468
151321.18+012502.2	2012-04-16	3600	19.45	18.18	18.28	18.17	18.05	17.34	17.01	16.36	15.81	2.865	2.825	quasar	2.753
152808.87+005211.8	2012-04-16	3600	18.97	18.11	18.09	18.07	17.95	17.20	16.89	16.54	16.12	2.675	2.675	quasar	2.610
153303.54+064032.9	2012-04-15	3600	22.74	18.99	18.43	18.35	18.26	17.84	17.26	16.81	16.15	3.405	3.350	quasar	3.422
153319.44+043257.3	2012-04-14	5400	18.81	18.10	17.99	17.96	17.74	17.28	17.08	16.74	15.95	2.535	2.575	low S/N	
153515.55+291038.5	2012-04-14	2700	19.08	17.71	17.50	17.36	17.30	16.79	17.29	16.17	16.10	2.905	2.775	F star	
153550.13+063352.8	2012-05-17	3600	19.08	18.43	18.32	18.32	18.12	17.90	17.57	17.15	16.37	2.535	2.275	low S/N	
153551.88+044416.4	2012-05-16	3600	18.73	18.19	18.03	18.01	17.92	17.79	17.50	17.02	16.13	2.535	2.275	quasar	2.377
153951.05+020133.8	2012-05-16	3600	18.90	18.31	18.24	18.21	18.08	17.32	17.11	16.78	16.13	2.365	2.575	quasar	2.569
154503.23+015614.7	2012-05-16	2700	18.36	17.90	17.64	17.65	17.51	17.03	16.71	16.21	15.42	2.505	2.225	low S/N	
162352.69+230119.6	2012-05-15	5400	20.15	19.21	18.79	18.45	17.96	17.20	16.57	16.08	15.76	2.715	2.925	low S/N	
162620.89+282924.7	2012-04-15	3600	19.20	18.42	18.32	18.33	18.17	17.39	17.04	16.81	16.30	2.605	2.675	quasar	2.534

Note: The SDSS *ugriz* magnitudes are given in AB system and the UKIDSS YJHK magnitudes are given in Vega system.

$z_{\text{ph1}}$ ,  $z_{\text{ph2}}$  and  $z_{\text{sp}}$  are the photometric redshifts obtained from the 5-band SDSS data by Richards et al. (2009) and obtained from the 9-band SDSS-UKIDSS data by us, and the spectral redshifts from our observations, respectively.

Table 2: Spectral parameters and black hole masses of 35 new quasars

Name (SDSS J)	Redshift	FWHM(CIV) ( $km\ s^{-1}$ )	$\log(L_{1350})$ ( $erg\ s^{-1}$ )	$\log(M_{BH})$ ( $M_{\odot}$ )	$\log(L_{bol})$ ( $erg\ s^{-1}$ )	$R_{EDD}$
081617.55+225604.5	2.931 $\pm$ 0.007	8460	46.392	9.783	47.057	-0.815
083255.70+004710.1	2.919 $\pm$ 0.007	4578	46.424	9.266	47.089	-0.267
084659.42+253940.9	2.892 $\pm$ 0.029	5121	46.569	9.441	47.234	-0.296
085825.51+283258.5	3.226 $\pm$ 0.008	5603	46.761	9.620	47.426	-0.284
090233.19+034131.2	2.532 $\pm$ 0.028	3677	46.243	8.980	46.908	-0.161
090827.71+011322.5	2.083 $\pm$ 0.081	6928	46.814	9.833	47.478	-0.444
091756.58+100836.7	2.760 $\pm$ 0.026	6057	46.825	9.722	47.489	-0.322
091857.36+025205.4	2.789 $\pm$ 0.038	8141	46.565	9.841	47.229	-0.701
092021.02-020113.7	2.826 $\pm$ 0.025	5565	46.557	9.506	47.221	-0.374
093655.11+305855.3	3.005 $\pm$ 0.012	4578	46.511	9.312	47.175	-0.226
094137.09+102650.9	2.584 $\pm$ 0.024	7050	46.475	9.668	47.140	-0.618
095118.43+083959.9	2.523 $\pm$ 0.006	6535	46.287	9.502	46.951	-0.640
100834.73-022302.5	3.086 $\pm$ 0.012	4578	46.338	9.220	47.002	-0.307
103301.49+065106.5	2.637 $\pm$ 0.027	4578	46.395	9.251	47.060	-0.280
114608.05+094216.5	2.580 $\pm$ 0.020	5567	46.180	9.307	46.845	-0.551
115531.45-014611.9	3.196 $\pm$ 0.047	4935	46.141	9.182	46.806	-0.465
121510.62+1428345	2.480 $\pm$ 0.073	7472	46.499	9.731	47.164	-0.657
122043.86+0111221	2.565 $\pm$ 0.042	12689	45.994	9.924	46.659	-1.354
122619.73+104953.5	2.375 $\pm$ 0.046	7294	46.478	9.699	47.142	-0.646
124605.36+071128.2	2.044 $\pm$ 0.019	7821	46.520	9.782	47.184	-0.687
125934.29+075200.7	2.370 $\pm$ 0.030	8670	46.882	10.063	47.546	-0.606
130318.32+030809.4	2.664 $\pm$ 0.037	4578	46.802	9.467	47.467	-0.089
131008.67+084405.0	2.232 $\pm$ 0.050	6460	46.550	9.632	47.214	-0.507
135942.50+022426.0	3.265 $\pm$ 0.014	6985	46.751	9.806	47.416	-0.480
142405.57+044105.5	2.232 $\pm$ 0.014	9870	46.582	10.017	47.247	-0.860
142543.33+024759.8	2.689 $\pm$ 0.035	5126	46.848	9.589	47.513	-0.166
142854.09+132259.0	3.093 $\pm$ 0.015	10575	46.002	9.770	46.667	-1.192
144526.15+023906.9	2.706 $\pm$ 0.017	6510	46.388	9.553	47.052	-0.590
145230.38+130227.3	2.468 $\pm$ 0.015	6345	46.275	9.471	46.940	-0.620
151321.18+012502.2	2.753 $\pm$ 0.035	4920	46.175	9.197	46.840	-0.446
152808.87+005211.8	2.610 $\pm$ 0.014	8608	46.251	9.723	46.915	-0.897
153303.54+064032.9	3.422 $\pm$ 0.021	8153	46.850	9.993	47.515	-0.568
153551.88+044416.4	2.377 $\pm$ 0.025	4578	46.408	9.257	47.072	-0.275
153951.05+020133.8	2.569 $\pm$ 0.028	7346	46.362	9.644	47.027	-0.707
162620.89+282924.7	2.534 $\pm$ 0.034	6978	46.484	9.664	47.148	-0.605



Table 3: A catalog of 7727 SDSS-UKIDSS quasar candidates with  $2.2 \leq z_{ph} \leq 3.5$  selected from R09

Name (SDSS J)	$z_{ph}(R09)$	$z_{ph}$	u	g	r	i	z	Y	J	H	K
000005.95+145310.1	2.255	2.725	21.31	20.64	20.45	20.19	19.93	19.41	18.83	18.51	17.76
000035.59-003146.1	2.255	2.725	21.63	21.04	20.83	20.4	20.36	19.19	18.92	18.31	17.51
000041.87-001207.3	2.905	2.925	21.02	19.62	19.44	19.32	19.19	18.45	18.14	17.56	16.86
000050.59+010959.1	2.605	2.575	19.85	19.08	19.02	19.09	18.89	18.33	18.17	17.69	16.9
000201.15+001707.4	2.465	2.475	21.48	20.77	20.69	20.65	20.18	19.71	19.36	18.77	17.68

Note: The SDSS *ugriz* magnitudes are given in AB system and the UKIDSS YJHK magnitudes are given in Vega system.  $z_{ph}(R09)$  and  $z_{ph}$  are the photometric redshifts obtained from the 5-band SDSS data by Richards et al. (2009) and obtained from the 9-band SDSS-UKIDSS data by us, respectively. Only a portion of the table is shown here. The whole table is available in the electronic version.

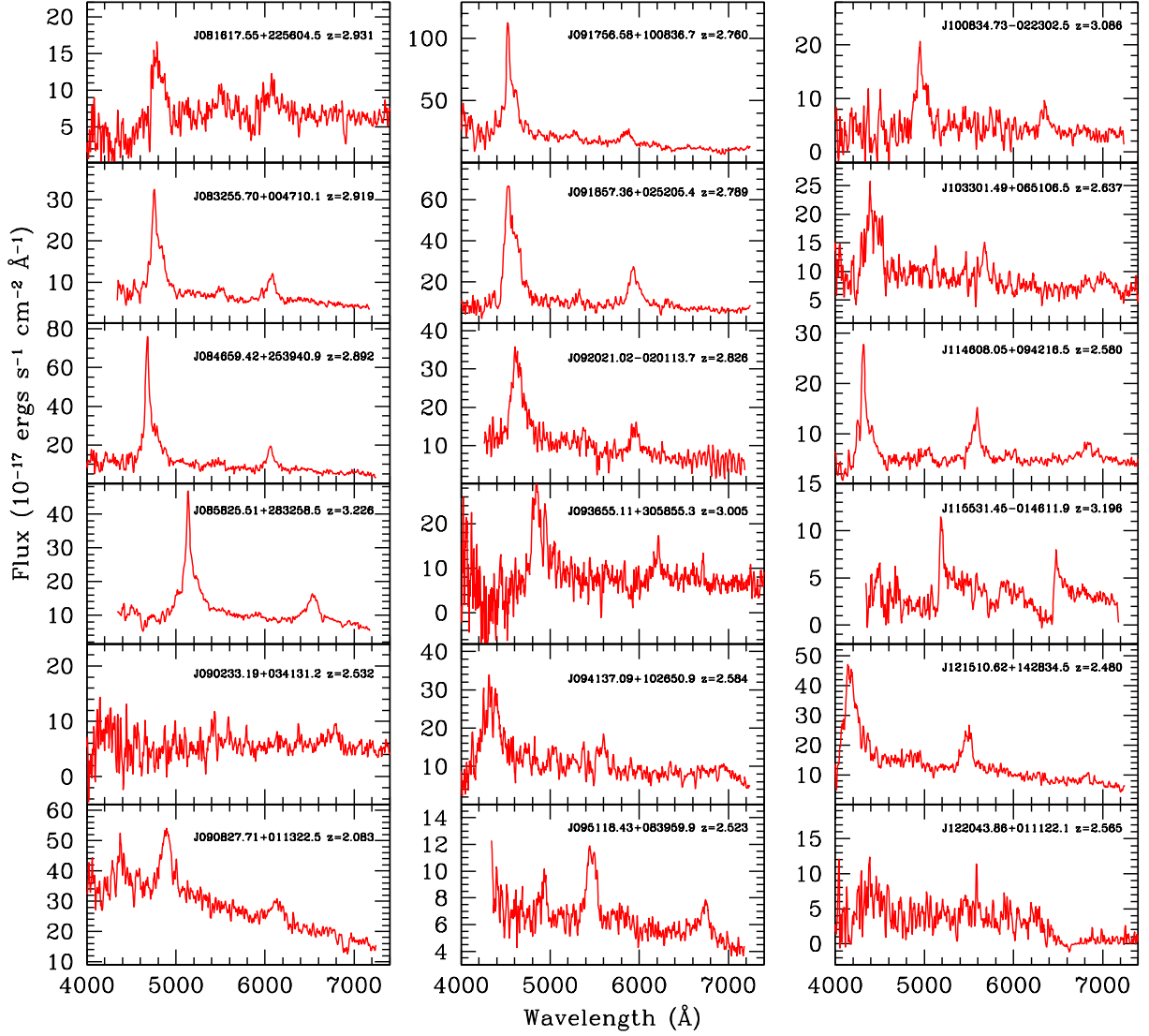


Fig. 1.— The spectra of the 35 new quasars at  $2.2 < z < 3.5$  identified with the BFOSC of the Xinglong 2.16m telescope, NAOC. The strongest emission line in each spectrum is  $\text{Ly}\alpha + \text{N V}$ .

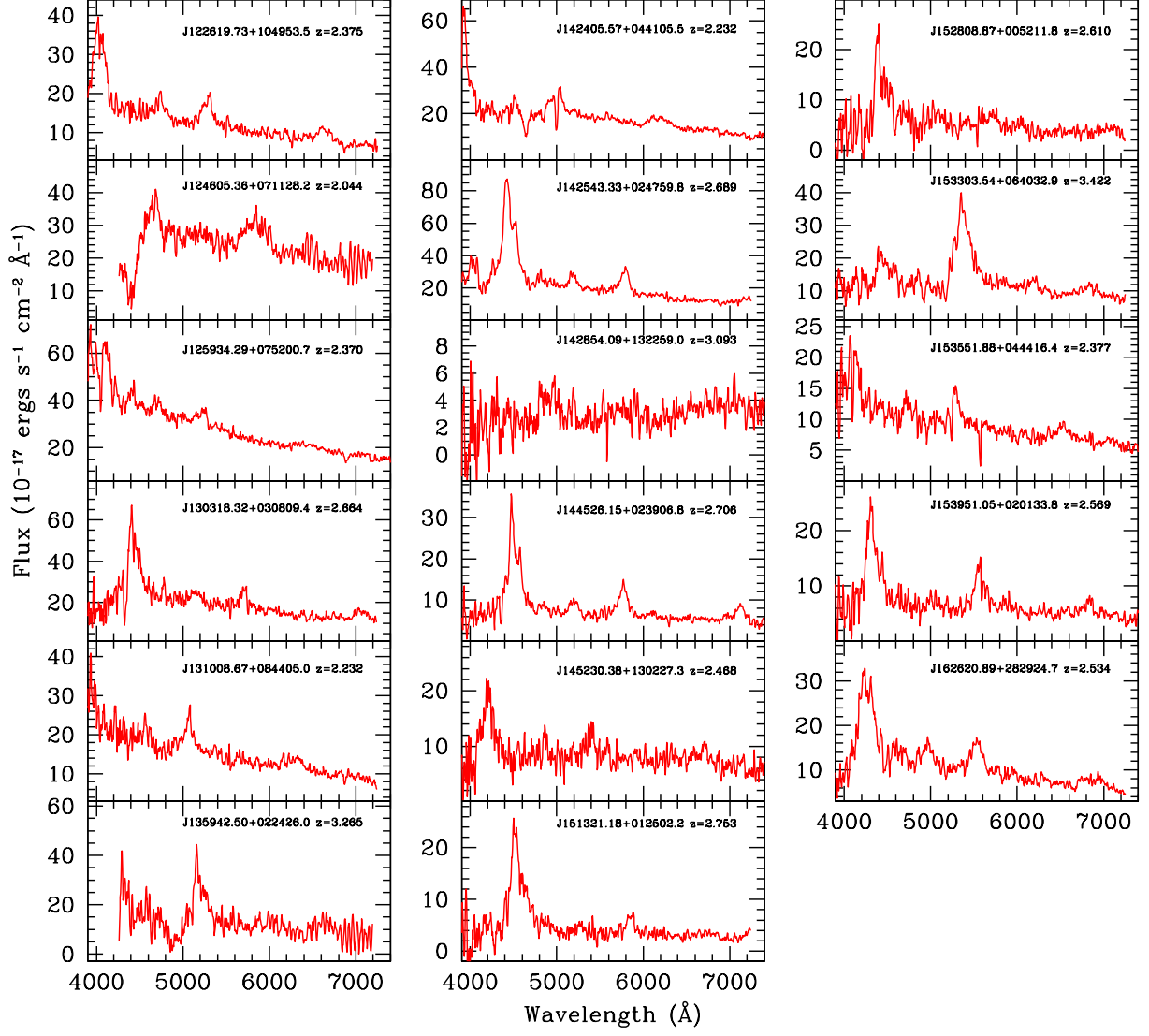


Fig. 1: (Continued)

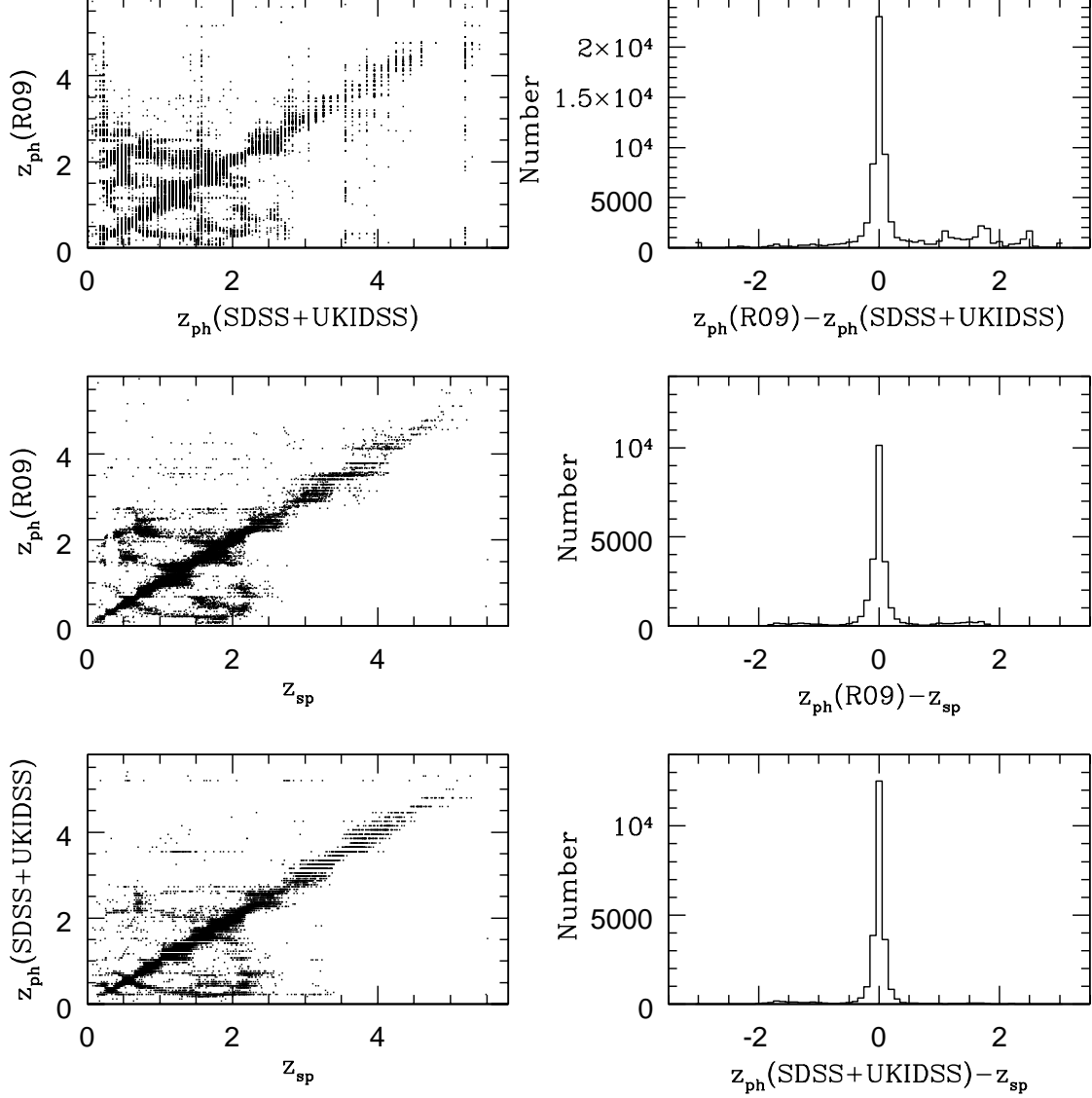


Fig. 2.— Upper panels: Comparison of the photometric redshifts in R90 and ours based on SDSS-UKIDSS 9-band data for 73011 unidentified quasar candidates in R09 and the histogram distribution of their differences. Middle panels: Comparison of the photometric redshifts in R90 with the spectral redshifts for 24878 known quasars and the histogram distribution of their differences. Lower panels: Comparison of the photometric redshifts given by us with the spectral redshifts for 24878 known quasars and the histogram distribution of their differences.

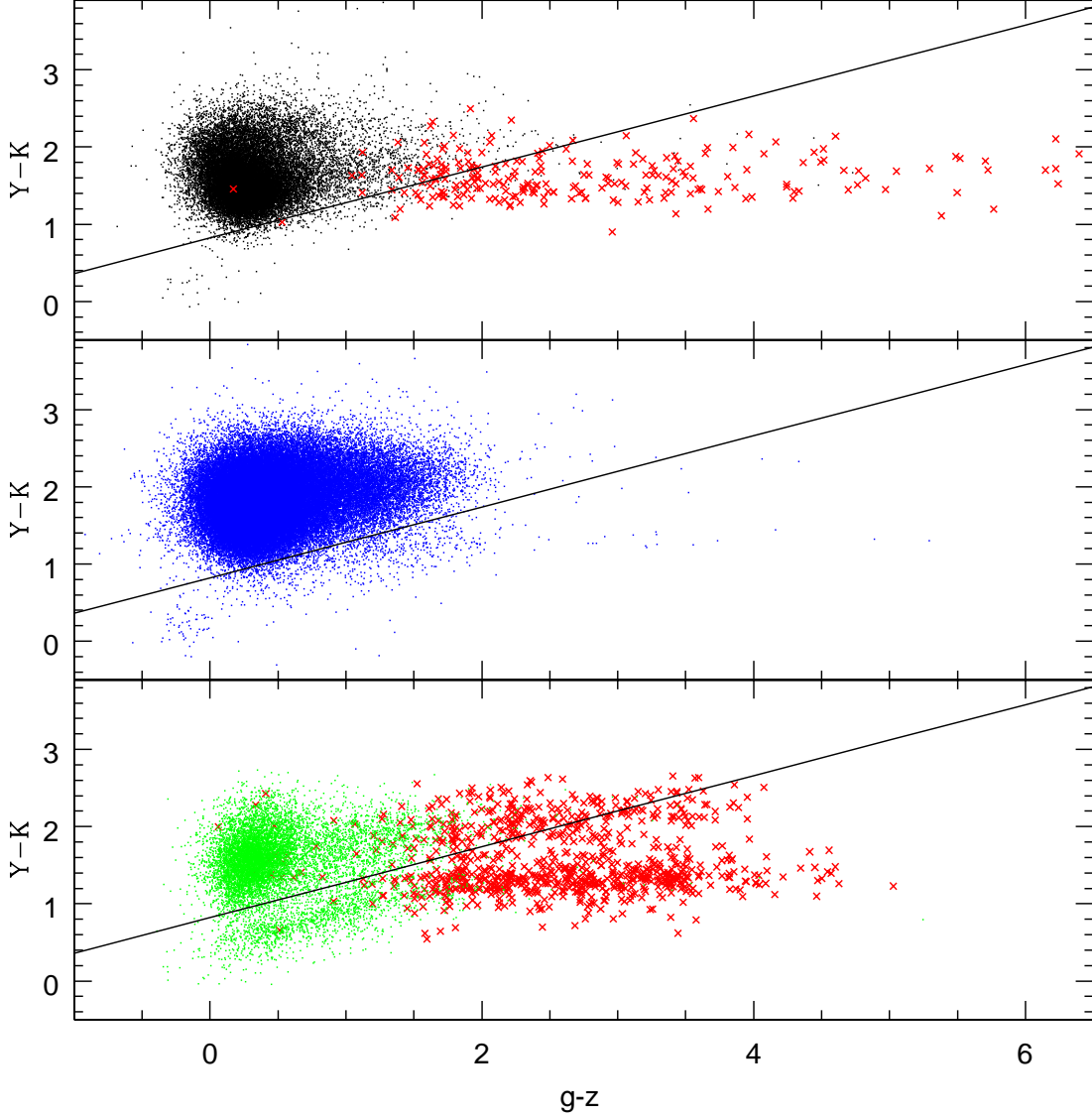


Fig. 3.— Upper panel: The distribution of 24878 known quasars in R09 in the Y-K/g-z color-color diagram. Black dots represent  $z < 4$  quasars and red crosses represent  $z > 4$  quasars. Middle panel: The distribution of 61489 unidentified quasar candidates in R09 with photometric redshift  $z_{ph} < 2.2$  in the Y-K/g-z color-color diagram. Lower panel: The distribution of 10687 unidentified quasar candidates in R09 with photometric redshift  $2.2 < z_{ph} < 4$  (green dots) and 835 unidentified quasar candidates in R09 with photometric redshift  $z_{ph} > 4$  (red crosses) in the Y-K/g-z color-color diagram.

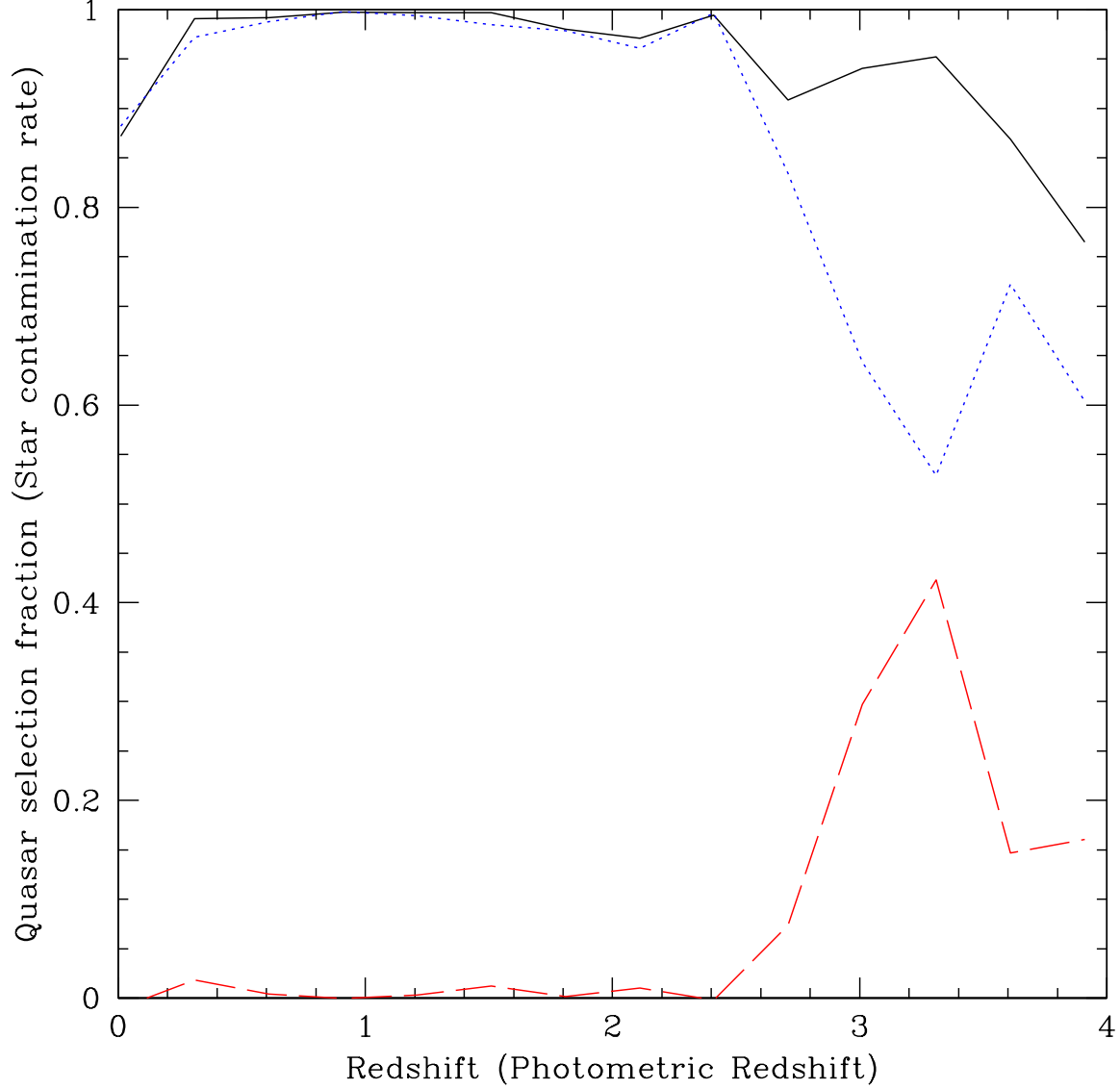


Fig. 4.— The black solid line denotes the redshift dependence of the fraction of 24648 known  $z < 4$  quasars in R09 selected by the Y-K/g-z criterion. The blue dotted line denotes the fraction of 72176 unidentified quasar candidates in R09 with photometric redshift  $z_{ph} < 4$  selected by the Y-K/g-z criterion as a function of photometric redshifts. The red dotted line denotes the possible star contamination rates of these unidentified quasar candidates in R09 at different photometric redshifts.